GEOFIZIKA VOL. 20 2003

Original scientific paper
UDC 551.465

Statistical approach to wind induced currents in the Northern Adriatic

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Received 8 August 2003, in final form 12 December 2003

Wind induced currents in the Northern Adriatic were analysed from a statistical point of view based on a 10 year long meteorological data set and a large amount of current-meter data measured in the same period at two stations. More than a hundred Bora and Sirocco episodes were averaged to typical Bora and Sirocco episodes. Using principal component analysis (PCA) it was found that the first four modes explain more than 80% of the total sea current variability. The first two modes describe about 50% of the current variability. There is a significant response of the first mode to Bora forcing and the second mode to Sirocco forcing, in good agreement with an earlier numerical model.

Keywords: northern Adriatic Sea, Bora, Sirocco, wind-driven currents, principal component analysis

Introduction

Over the Adriatic sea the strongest winds blow mainly in winter. Two of the most frequent winds are Bora and Sirocco. The Bora wind is a cold dry wind blowing from ENE direction with a mean speed reaching 15 m/s at some locations (Duplančić, 1959). The Sirocco blows from a SE direction with a typical speed of 10 m/s. Sirocco transports warm and moist air from the Mediterranean, usually accompanied by precipitation. Both winds are transient occurrences with a typical duration of several days.

Sea level response to Bora wind was observed for the first time by Mazelle (1896). He also observed sea level response to Sirocco wind in 1895 that was later documented by other authors (Sterneck, 1904; Kesslitz, 1911; Polli, 1968; Mosetti and Bartole, 1974).

The first observations of Bora-induced sea currents were again documented by Mazelle (1915). The analyses of simultaneous time series for wind and sea currents show that the Bora significantly, although transiently, contributes to the current field of the Adriatic (Kuzmić et al., 1985; Orlić et al., 1986; Zore-Armanda and Gačić, 1987). Mosetti and Mosetti (1990) compared sea currents measured in Trieste bay with (Bora) wind speed in winter 1984–1985. They found that the surface current speed is about 3% of the wind speed, and the direction of currents is rotated to the right of wind direction by about 25°, but these results are valid only for measurement at fixed points, not for the entire area of Gulf of Trieste. These currents are part of the Bora wind driven basin-scale gyre (*e.g.* Stravisi, 1983).

Some characteristics of the Adriatic Sea response to Bora wind are reproduced by numerical models; a two-dimensional model for the northern Adriatic (Stravizi, 1977), two-layer model for the shelf south of the Po river delta (Malanotte-Rizzoli and Bergamasco, 1983) and three-dimensional models for the northern Adriatic (Kuzmić and Orlić, 1987; Bone, 1993). Orlić et al. (1994) gave a numerical model of the Adriatic Sea response to Bora and Sirocco winds and compared numerical results with in *situ* measurements. Kuzmić (1986) suggested the possibility of improving numerical and empirical data fitting using a depth-dependent coefficient of turbulent viscosity. Kuzmić and Orlić (1987) showed the upwind current during the Bora wind episode along the Po river delta – Rovinj transect by numerical simulations, and confirmed it by direct measurement. The Coastal Zone Color Scanner (CZCS) satellite image recorded on 26 March 1982 after one Bora episode, clearly shows the transport of a high pigment by concentration from the Po delta eastward as the numerical model predicts (Kuzmić, 1991).

Brana et al. (1996) analysed meteorological and current-meter data at three stations in the northern Adriatic during winter 1992–93. Over the measurement period two Sirocco and three Bora episodes occurred. During Sirocco episodes currents were down wind, while during Bora episodes currents west of Rovinj were upwind, in accordance with the numerical model (Orlić et al., 1994).

Large amounts of current-meter data measured at two stations in the northern Adriatic in the period 1984–1993 enabled a statistical approach to wind induced currents in the area and form the basis for results presented in this paper. In other words, a large number of Bora and Sirocco episodes during the measurement period were not analysed individually, but are pooled together in order to reconstruct a typical, average Bora and Sirocco episode and average wind-driven currents with appropriate statistical significance.

Data

Sea currents have been measured at two stations, refered to as SJ107 and SJ209, in the period 1984–1993. The station SJ107 is located about 15 nautical miles west of Rovinj where the depth is 37 m, while the station SJ209 is located about 15 nautical miles west of Pula where the depth of the sea-floor is 43 m (Fig. 1). Currents were measured at two depths at both stations; 5 m under the surface and 5 m above the bottom with the Aanderaa RCM4 current-meters. The sampling interval was 10 minutes.

Meteorological parameters were measured at Istituto Sperimentale Talassografico in Trieste (45° 38' 34" N, 13° 45' 14" E). Meteorological parameters used in this work are the mean, maximal and minimal daily values of atmospheric pressure, air temperature, relative humidity, mean and maximum wind speed, direction of wind, precipitation, evaporation, global radiation and the sea temperature at 2 m depth for the period starting from 1 January 1983 to 31 December 1992.

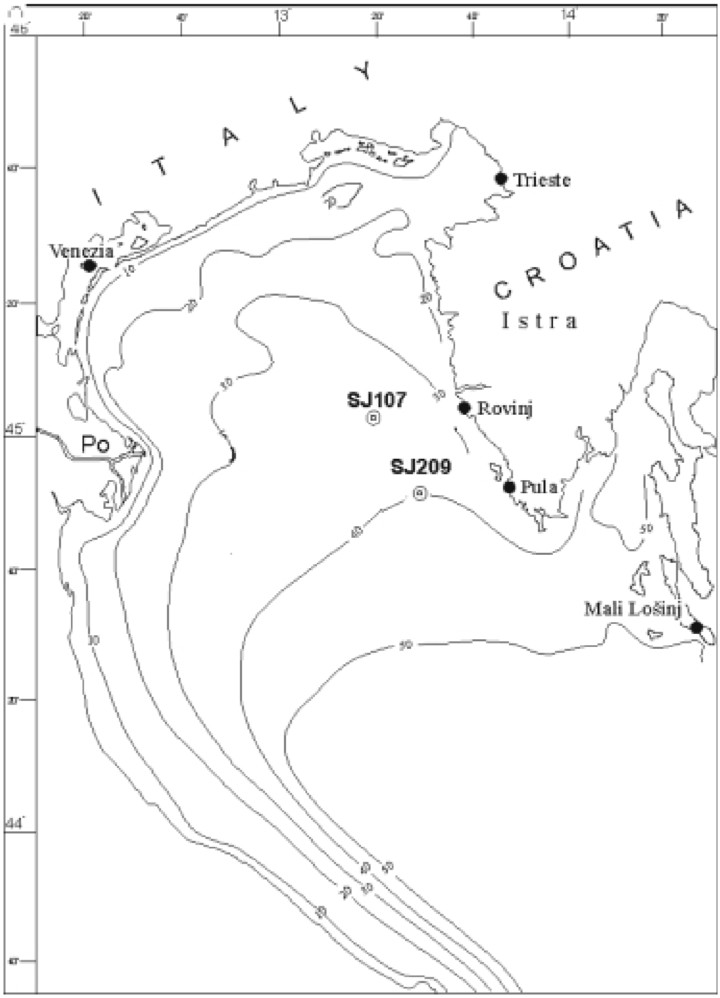

Figure 1. Map of the northern Adriatic with positions of two current-meter stations (SJ107 and SJ209) and the meteorological station in Trieste.

Methods

Meteorological parameters over the period of 10 years were initially fitted with the first six Fourier harmonics of which the fundamental period is of 365.25 days. Anomalies were then calculated by removing these cycles from the original data.

In order to determine intervals in days with the strong (anticyclonic) Bora, only days with the mean daily wind speed greater than 5 m/s and in the ENE direction, with maximal wind speed greater than 20 m/s, without precipitation and with a negative relative humidity anomaly were chosen. Two or more consecutive days that satisfied these conditions were treated as a single Bora episode. For every Bora episode the day with maximal mean wind speed was selected as the 0-day.

Since Trieste is sheltered from direct Sirocco wind influence, Sirocco episodes were not determined by the same method as for the Bora wind. Instead cyclonic Sirocco episodes were determined by analysis of other meteorological parameters. The intervals of Sirocco were defined as those for which the atmospheric pressure was falling, relative humidity anomaly was positive, evaporation anomaly was negative and there was precipitation. The 0-day is selected as the day with maximum precipitation.

All Bora and Sirocco episodes were pooled together and the meteorological parameters were averaged starting from 5 days before to 5 days after the episode maximum. For each of 11 days and for all parameters, mean values of anomalies and standard errors of the mean were determined.

From the current meter time series data hourly mean eastward (u) and northward (v) components were calculated. Seven principal tidal constituents were determined and extracted from the hourly time series. In the next step inertial oscillations were synthesised and extracted using a complex filter defined in Krajcar and Orlić (1995). The u and v components of time series, without tidal and inertial signals, were finally low passed using moving average filters with a period of 23 and 25 hours in order to eliminate other high-frequency signals. From these filtered time series daily values were determined.

Since two components of currents were measured at two stations at two depths, this gives a total of 8 components. These eight components are mutually dependent with a high correlation among them, so it is possible to use principal component analysis (PCA) to find the orthogonal modes as eigenvectors of the eight components correlation matrix, and to examine the response of these mode scores to wind forcing.

In the next step, intervals when currents were measured during episodes of Bora and Sirocco were selected. These episodes were pooled together in order to determine the response of sea currents to wind forcing. For every period of 11 days, mean value and standard error means of four mode scores were calculated.

The significance of parameters in the 11 days mean time series was examined by a simple Monte Carlo method (*e.g.* Fang et al., 2002). The evolution of some parameter mean within the period of 11 days of an average Bora or Sirocco episode is determined as an average of n individual episodes. In order to determine the 95% confidence limits, $100 \times n$ 11-day periods were randomly selected (using a unitary random number generator) and a total of 1100 mean parameter values were determined. These data were sorted and finally, for the 95% confidence limits, the 27th and 1074th values were selected.

Results and discussion

Using the criteria introduced in the previous section 161 days (in 108 episodes) of strong Bora wind were selected from a 10-year period. The 0-day of an episode was the day with the strongest Bora wind. The time evolution of meteorological parameters (anomalies) measured in Trieste starting 5 days before and lasting to 5 days after the wind speed maximum are presented in Fig. 2.

Before the average Bora episode the atmospheric pressure was about 2 hPa below the mean value. During Bora the pressure rise was of about 3 hPa. The temperature decreased during the Bora episode by about 2.5 degrees and relative humidity was about 20% lower than that at days without Bora. Global radiation during Bora was for about 2.5 MJ/m^2 greater than during the calm because of the absence of clouds. Evaporation is about 1.2 mm larger and the sea temperature decreases by about 0.7 degrees due to Bora cooling and vertical mixing of the upper layer. The mean daily wind speed during a Bora episode is about 5 m/s greater than during the days without Bora and the maximum wind speed anomaly increases to 17 m/s for the 0-day (the mean of daily maximum speed was about 28 m/s at 0-day).

The criteria used for determination of Sirocco episodes satisfied 197 days over the 10-year period. Sirocco episodes were determined without the use of wind direction and speed, but using other meteorological characteristics of Sirocco (Fig. 3). The 0-day was selected as the day with maximum precipitation. During a Sirocco episode the atmospheric pressure falls, the air temperature anomalies do not show significant changes, relative humidity is greater by about 15%, average precipitation is about 15 mm on the 0-day. Global radiation was lower by 7 MJ/m^2 due to clouds and the evaporation anomaly was negative (a minimum of –0.5 mm). There is no significant response of the sea temperature to Sirocco in Trieste. It is interesting to note that during these average Sirocco episodes the daily mean and maximal speed (in Trieste) is lower than on other days, because Trieste is sheltered from direct Sirocco wind influence, while at the same time there is strong Sirocco wind blowing from a SE direction in the open northern Adriatic.

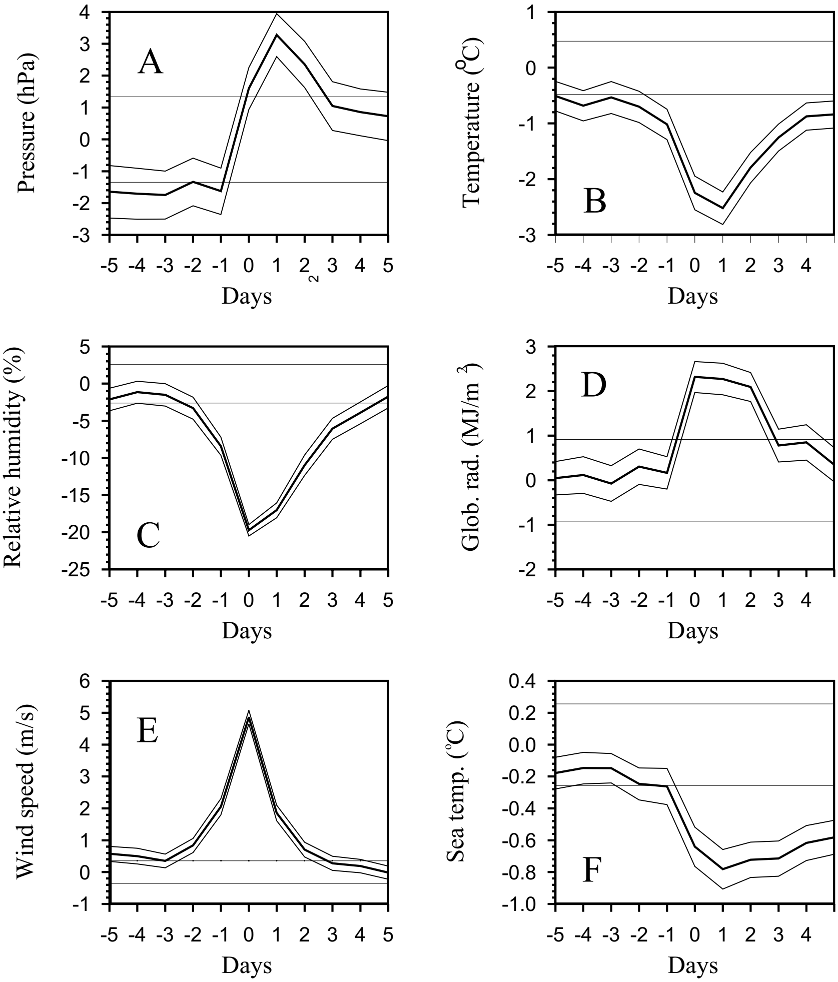

Figure 2. Evolution of meteorological parameters during a typical Bora episode. Thick lines represent the mean anomaly of meteorological parameters, thin lines represent standard error of the mean range while the two horizontal thin lines show the 95% confidence limits. A: Air pressure anomaly. B: Air temperature anomaly. C: Relative humidity anomaly. D: Global radiation anomaly. E: Scalar wind speed anomaly. F: Sea surface temperature anomaly.

Although the mean daily wind speed is nearly constant throughout the year (about 3 m/s mean daily speed and about 10 m/s maximum speed), the selected days of strong Bora wind occurred mainly during the winter period and were very rare in summer (Fig. 4).

Days of Sirocco wind occurred mainly during the winter period and were very rare in summer, similar to the situation with strong Bora wind (Fig. 4).

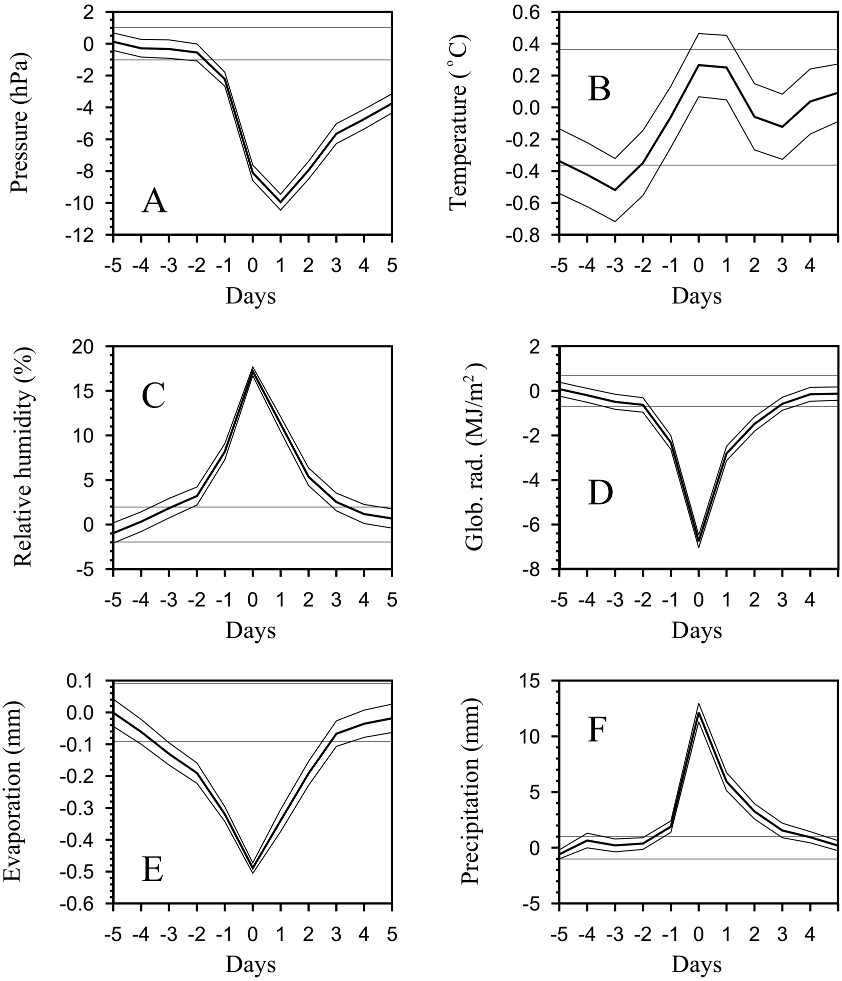

Figure 3. Evolution of meteorological parameters during a typical Scirocco episode. Thick lines represent the mean anomaly of meteorological parameters, thin lines represent standard error of the mean range while the two horizontal thin lines show the 95% confidence limits. A: Air pressure anomaly. B: Air temperature anomaly. C: Relative humidity anomaly. D: Global radiation anomaly. E: Evaporation anomaly. F: Precipitation anomaly.

From simultaneous measurements at stations SJ107 and SJ209 eight current components are presented as orthogonal modes of modal decomposition using the PCA method. It was found that the first four modes explain about 80% of total sea current variability (Fig. 5). The Bora and Sirocco responses for these four orthogonal modes were determined. No significant response for the third and fourth mode to wind forcing was found, but there was significant response of the first mode score to the Bora wind and a signif-

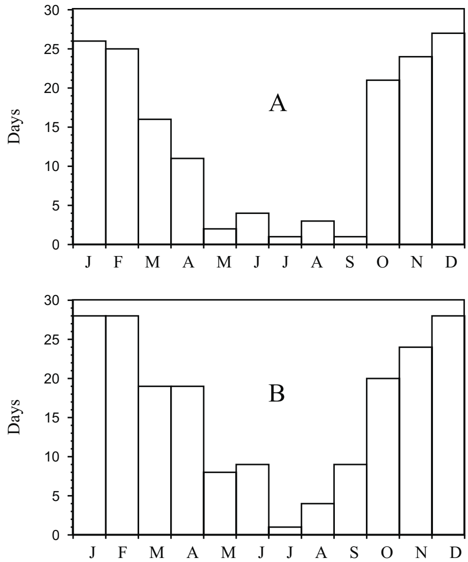

Figure 4. A: Annual distribution of Bora days within each month that occured over the 10-year period. B: Annual distribution of Scirocco days within each month that occurred over the 10-year period.

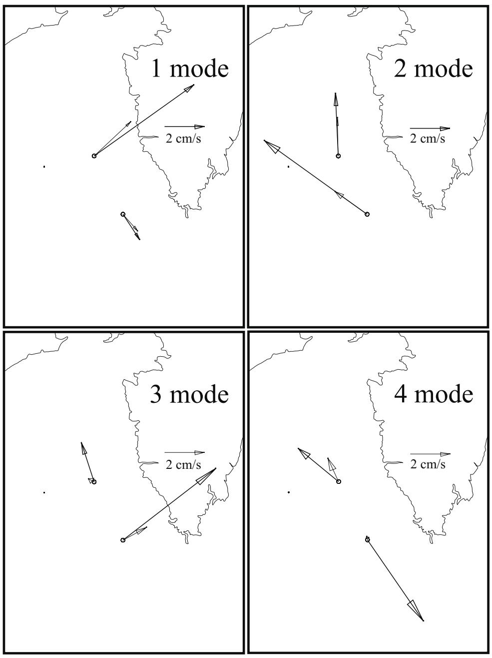

Figure 5. Four orthogonal modes of currents at two stations and at two depths. Thick vectors represent surface currents and the thin ones represent bottom currents.

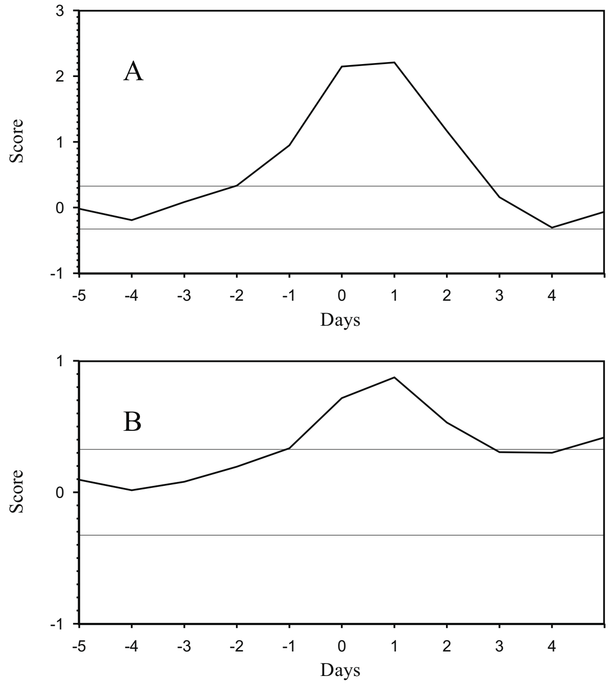

Figure 6. A: Evolution of the first mode score during an average Bora episode. B: Evolution of the second mode score during an average Scirocco episode. Thick line represents the mean score while the two horizontal thin lines show the 95% confidence limits.

icant response of the second mode to Sirocco forcing (Fig. 6). It can be concluded therefore that the first mode represents sea response to Bora, whereas the second mode represents the sea response to Sirocco wind.

Scores of the first and second modes are greater than one mainly during the winter period, *i.e.* in the period of Bora and Sirocco episodes, so it can be concluded that wind induced current contributions to the global circulation is maximal in the winter period and minimal in summer period.

These results may be compared to an earlier numerical model (Orlić at al., 1994) where a numerical analysis of Adriatic sea response to typical winds in the area (Bora and Sirocco) is presented. In this numerical model there is a cyclonic gyre in the north and an anticyclonic gyre south of the Po river delta-Rovinj line as a sea response to the nonuniform Bora wind field. It is interesting to note that on the Po river delta – Rovinj line, where the wind is minimal, the sea currents direction is towards the east, opposite to the wind. This is in accordance with the current direction at station SJ107 for the first (Bora) mode. In the numerical model there is northerly circulation near the Istrian peninsula for the Sirocco episode, again in accordance with these results (directions of currents at two stations for the second mode).

Conclusions

In this work the wind induced currents in the Northern Adriatic were analysed from a statistical point of view based on a 10 years long meteorological data set measured at Trieste and a large quantity of current-meter data measured in the same period at two stations in the Northern Adriatic.

From meteorological data more than a hundred Bora and Sirocco episodes were selected. These 11 days long episodes were pooled together in such a way that for the 0-day of a Bora episode the day with maximal wind speed was selected and for a Sirocco episode 0-day was selected as the one with maximal precipitation. In such a way the typical (average) Bora and Sirocco episodes were determined with time evolution of meteorological parameters starting from 5 days before to 5 days after the episode maximum (0-day). It was found that after strong Bora the sea (surface) temperature at Trieste decreased significantly.

From the original current meter data tidal currents were first determined and extracted together with inertial oscillations and other high-frequency oscillations and daily values were determined. In applying the PCA method on filtered data it was found that the first four modes explain more than 80% of the total current variability.

Significant responses of the first mode to Bora forcing and the second mode to Sirocco forcing are in agreement with the earlier numerical model (Orlić at al., 1994).

Therefore, the first mode may be interpreted as a response to the Bora, and the second mode as a response to the Sirocco wind. These two modes describe about 50% of total sea current variability.

Bora and Sirocco episodes occurred mainly over the winter period and the first (Bora) and second (Sirocco) modes also had scores greater than one mainly in winter period. It may be concluded that the contribution of wind induced currents to global circulation is maximal in the winter period and minimal in the summer period.

Acknowledgements – This research was supported by the Ministry of Science and Technology of the Republic of Croatia project no. 0098113.

References

Bone, M. (1993): Development of a non-linear levels model and its application to bora-driven circulation on the Adriatic shelf. Estuarine, Coastal and Shelf Science, **37**, 475–496.

Brana, J. H., Krajcar, V., Morožin, D., and Supić, N. (1996): Circulation and heat exchanges of the Northern Adriatic in the winer season 1992/93. Il Nuovo Cimento, **19**, 427–440.

Duplančić, K. Č. (1959): On Adriatic climate and weather (in croatian language). Hidrografski godišnjak 1958*,* **9**, 225–250

Fang, K.-T., Hickernell, F. J. and Niederreiter, H., (editor) (2002): Monte Carlo and Quasi-Monte Carlo Methods 2000. Springer-Verlag, New York, 500 pp.

Kesslitz, W. (1911): Die Sturmflut am 15. und 16. November 1910 in Pola. Mitteilungen aus dem Gebiete des Seewesens, **39**, 157–163.

Krajcar, V. and Orlić M., (1995): Seasonal variability of inertial oscillations in the Northern Adriatic. Continental Shelf Research, **15**, 1221–1233.

Kuzmić, M., Orlić, M., Karabeg, M. and Jeftić, Lj. (1985): An investigation of wind-driven topographically controlled motions in the Northern Adriatic. Estuarine, Coastal and Shelf Science, **21**, 481–499.

Kuzmić, M. (1986): Wind curl *vs* variable eddy viscosity: A Northern Adriatic related modelling study. Geofizika, **3**, 63–74.

Kuzmić, M. and Orlić, M. (1987): Wind-induced vertical shearing: ALPEX/MEDALPEX data and modelling exercise. Annales Geophysicae, **5B**, 103–112.

Kuzmić, M. (1991): Exploring the effects of bura over the northern Adriatic: CZCS imagery and mathematical model prediction. International Journal of Remote Sensing Letters, **12**, 207–214.

Malanotte-Rizzoli, P. and Bergamasco, A. (1983): The dynamics of the coastal region of the Northern Adriatic Sea. Journal of Physical Oceanography, **13**, 1105–1130.

Mazelle, E. (1896): Einfluss der Bora auf das Meeresniveau. Meteorologische Zeitschrift, **13**, 68–70.

Mazelle, E. (1915): Meeresstömungen und Winde in der Adria. Meteorologische Zeitschrift, **32**, 222–227.

Mosetti, F. and Bartole, R. (1974): Esame dell'effetto del vento sui solevamenti di livello dell' Adriatico settentrionale. Rivista italiana di geofisica, **23**, 71–74.

Mosetti, F. and Mosetti, P. (1990): Measurement on wind driven circulation in the North Adriatic Sea. Bollettino di Oceanologia Teorica ed Applicata, **8**, 251–261.

Orlić, M., Chiasmic, M. and Vučak, Z. (1986): Wind-curl currents in the Northern Adriatic and formulation of bottom friction. Oceanologica Acta, **9**, 425–431.

Orlić, M., Kuzmić, M. and Pasarić, Z. (1994): Response of the Adriatic Sea to the bora and sirocco forcing. Continental Shelf Research, **14**, 91–116.

Polli, S. (1968): L'eccezionale acqua alta nella laguna di Venezia in relazione agli ultimi eventi idrometeorici. Quaderno-Accademia nazionale dei Lincei, **112**, 63–78.

Sterneck, R. (1904): Kontrolle des Nivellements durch die Flutmesserangaben und die Schwankungen des Meeresspiegels der Adria. Mitteilungen des K. u. K. Militärgeographischen Institutes, **24**, 75–141.

Stravisi, F. (1977): Bora driven circulation in Northern Adriatic. Bollettino di Geofisica Teorica ed Applicata, **19**, 95–102.

Stravisi, F. (1983): Some characteristics of the circulation in the Gulf of Trieste. Thalassia Jugoslavica, **19**, 355–363.

Zore-Armanda, M. and Gačić, M. (1987): Effects of bura on the circulation in the North Adriatic. Annales Geophysicae, **5B**, 93–102.

SAŽETAK

Statistički pristup vjetrovnim strujama u sjevernom Jadranu

Valter Krajcar

Analizirane su vjetrovne struje u sjevernom Jadranu koristeći statistički pristup temeljen na desetogodišnjim meteorološkim podacima i obimnom skupu strujomjernih podataka izmjerenih u istom razdoblju na dvije postaje. Više od stotinu epizoda bure i juga usrednjeno je u prosječne epizode. Koristeći metodu glavnih komponenata pronađeno je da prva četiri moda opisuju više od 80% ukupne varijabilnosti morskih struja. Prva dva moda opisuju oko 50% ukupne varijabilnosti struja. Statistički je značajan odziv prvog moda na buru te drugog moda na jugo, u izvrsnom slaganju s ranijim numeričkim modelom.

Ključne riječi: sjeverni Jadran, bura, jugo, vjetrovne struje, metoda glavnih komponenata

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